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HIGH-TEMPERATURE LIQUID-MERCURY
CATHODES FOR ION THRUSTORS

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I. INTRODUCTION AND SUMMARY

The main purpose of this contract is to develop liquid-mercury cathodes^{*} capable of satisfactory operation in Kaufman-type thrusters^{**} up to temperatures high enough to be compatible with the highest thruster shell temperatures anticipated under the unfavorable thermal conditions of a clustered array of thrusters. The achievement of this objective is desirable because of the favorable characteristics of LM(Hg) cathode thrusters such as practically unlimited cathode life, invariance of thruster characteristics, and excellent thruster performance, together with the advantages inherent to the use of mercury as a propellant^{***}.

LM(Hg) cathode operation compatible with high thruster shell temperatures is achieved both by increasing the permissible operating temperature of the LM cathode and by reducing the total thermal load of

* The liquid-mercury cathode referred to here is a gravity-independent, force-fed liquid-metal cathode invented and developed at the Hughes Research Laboratories (see: W. O. Eckhardt: Liquid-Metal Arc Cathode. Patent applied for). For brevity, we shall refer to this cathode in general as the Liquid-Metal or LM cathode; to refer to a particular liquid metal, its chemical symbol is added in parenthesis, e.g., LM(Hg) cathode in the case of mercury.

** W. O. Eckhardt, J. A. Snyder, H. J. King, and R. C. Knechtli, "A New Cathode for Mercury Electron-Bombardment Thrusters," AIAA Paper No. 64-690 (August 1964).
H. J. King, W. O. Eckhardt, J. W. Ward, and R. C. Knechtli, "Electron-Bombardment Thrusters using Liquid-Mercury Cathodes," AIAA Paper No. 66-232 (March 1966).

*** W. O. Eckhardt, H. J. King, J. A. Snyder, J. W. Ward, W. D. Myers, and R. C. Knechtli, "4,000-hr Life Test of a Liquid-Mercury Cathode in a 20-cm LeRC Ion Thruster," Hughes Research Laboratories Special Report for Contract NAS 3-6262 (Nov. 1966).

the cathode. While increases in permissible operating temperature result from design improvements of the cathode proper, the thermal load reduction is achieved by modifications of the electron and atom flux coupling between cathode and discharge chamber; the latter lead to a lower optimum electron-to-atom emission ratio and are also intended to increase the thruster efficiency. Progress along both lines of approach depends strongly on the understanding of cathode and discharge-chamber phenomena, thus requiring measurements of the pertinent parameters of cathode and discharge-chamber operation.

Stable, long run operation of high-temperature cathodes as well as excellent thruster performance with high-temperature cathodes has been demonstrated during this quarter. The most important achievement was the demonstration of thruster performance with high-temperature cathodes closely approximating the best obtained with low-temperature cathodes: 87% mass utilization with 400 eV/ion at 250°C cathode temperature, and 84% mass utilization with 443 eV/ion at 300°C cathode temperature. Further improvements can be expected from the presently planned cathode modifications.

II. HIGH-TEMPERATURE LM CATHODE DEVELOPMENT

A. Modifications of Cathode Geometry

During the past quarter, Annular Cathode No. 25 has been reworked to achieve the geometry of the mercury flow passage described in Quarterly Progress Report No. 1, p. 18 (a narrow passage of minimum depth, fed by a wider passage). As intended, this geometry now permits the rapid re-establishment of a full-circle arc spot pattern whenever the discharge is interrupted while the cathode is operating at high temperature. This feature is very important because optimum high-temperature cathode performance depends on the even distribution of the thermal power delivered to the cathode.

In order to measure the thermal power delivered to the cathode by the discharge, two thermistor elements, forming part of a bridge circuit, have been designed into the input and output of the cooling gas lines. This allows sensitive monitoring of changes in the heating power as pertinent parameters and the geometry are changed.

To improve the accuracy of our thermal power measurements, helical grooves were machined into the cylindrical surfaces of the cone assemblies of Annular Cathodes No. 25 & 26. Coaxial-type electric heaters were press-fitted into this groove. A controller, connected to the cathode thermocouple, adjusts the average current through this heater so that the cathode temperature remains constant (at a constant cooling gas flow rate), whether or not the cathode is operating. The gas flow is then adjusted so that the heater is completely off when the cathode operates at the intended discharge current, and a reading of the thermal power delivered to the cooling gas is taken (using the thermistor bridge). This reading is subsequently calibrated by turning the discharge off and measuring the electrical power to the heater.

Besides permitting more accurate power measurements, this arrangement also keeps the cathode temperature far more constant than the methods previously employed during experiments where the discharge current or the mercury feed rate are being varied.

An additional advantage of the heater on the cathode circumference is that the entire cathode can be outgassed at up to 600°C. The metallic O-ring seal for the flow impedance (see Quarterly Progress Report No. 1, Fig. 3) permits such bakeouts. Outgassing of the cathode at elevated

temperature after exposure to air showed a decided benefit in subsequent operation: it leads to a much faster establishment of a stable full-circle arc spot pattern.

It should be emphasized that all three advantages of having a heater on the cathode pertain only to experimentation with the cathode; no heater would be required on cathodes for actual operation in space.

Other modifications affect not the cathode proper but the non-magnetic inserts which provide the transition between cathode and magnetic thruster end plate (for permanent-magnet thruster geometries) or between cathode and magnetic shield (for electromagnet thruster geometries). These inserts have been reshaped so as to minimize heating of the cathode body by ion bombardment from the discharge (see, for example, Fig. 1).

B. -Test Results in Diode Operation

A continuous run (i. e., no arc extinctions) was made in the diode configuration with Annular Cathode No. 25 at 300°C and $K_e/K_a = 10$ for 4-1/2 hours. The arc current was 8.6 A, suitable for 20-cm thruster operation. It is felt that only one or two automatic arc starts would have easily extended this run to 24 hours or more. (The test facilities are not equipped with automatic starting circuits as yet.)

Annular Cathode No. 26 was equipped with the same non-magnetic insert geometry used on the life-test cathode (see Fig. 1). A subsequent run in the diode configuration clearly indicated improvement over past data on this cathode. An arc current of 9.8 A was run for 4-1/2 hours at 300°C with a K_e/K_a of 16. The cathode temperature rose at one point to 350°C and again to 325°C without extinguishing. This result indicates that with suitable adjustment, the performance at a steady 300°C could be even better. This cathode has not had the mercury feed gaps shortened yet and accordingly is harder to ignite or restart than No. 25, at any given temperature.

The flow passages of Cathode No. 26 will now be modified in the same way as those of No. 25. The resulting geometry should then combine the present relative advantages of both cathodes.

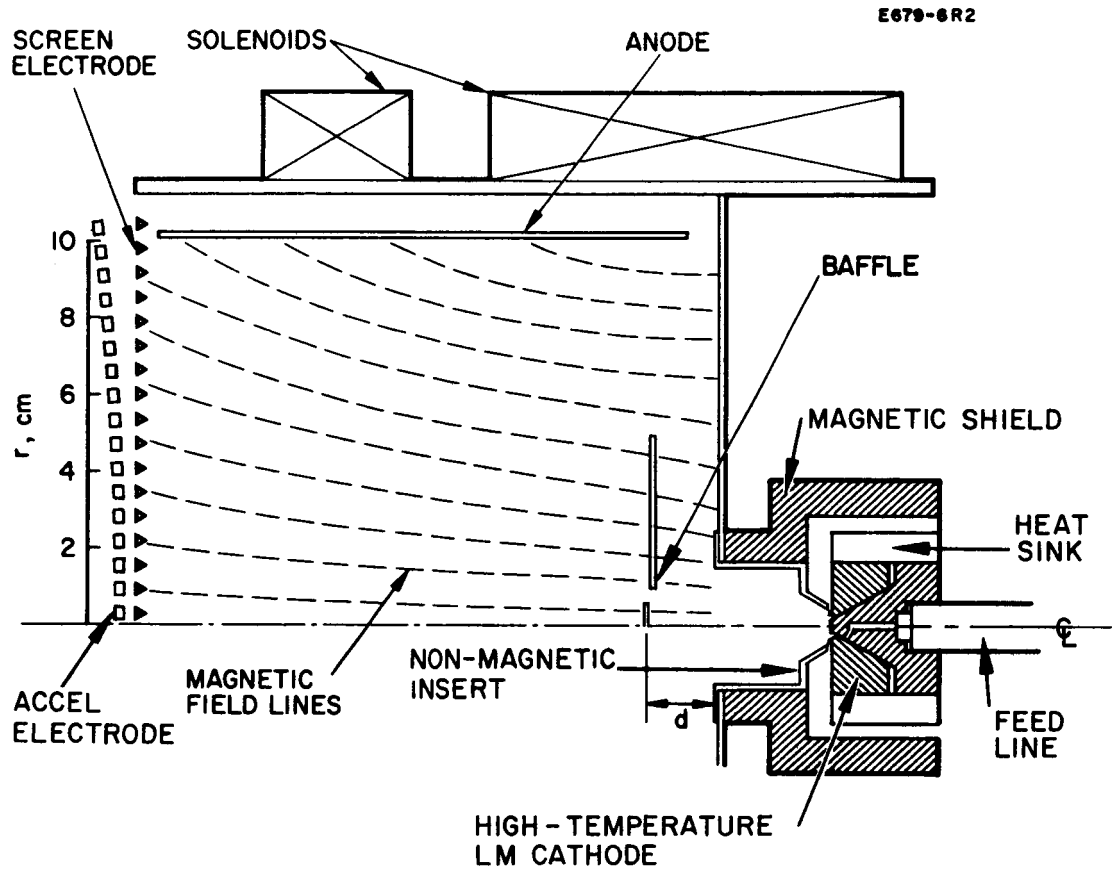


Fig. 1. Schematic cross section of 20-cm diameter electron-bombardment thruster with high-temperature LM cathode.

The thermal power measurements have shown that the ratio of heating power to discharge current increases significantly when the arc spot pattern is being withdrawn deeply into the narrow annular gap of the pool-keeping structure. For example, with Annular Cathode No. 25 operating at a discharge current of ≈ 5 A and $K_e/K_a \approx 10$, the specific heat load is

$$2.3 \text{ WA}^{-1} @ 127^\circ\text{C},$$

$$4.7 \text{ WA}^{-1} @ 250^\circ\text{C},$$

$$\approx 9 \text{ WA}^{-1} @ 300^\circ\text{C}.$$

On the other hand, with Annular Cathode No. 26 (which differs from No. 25 by a 3-fold increase in the mean diameter of the annulus and a 2.5-fold reduction in gap width) at the higher current of 9.8 A and the higher $K_e/K_a = 16$ the following specific heat loads were measured:

$$2.3 \text{ WA}^{-1} @ 127^\circ\text{C},$$

$$6.1 \text{ WA}^{-1} @ 300^\circ\text{C}.$$

This shows clearly the advantages of operation at a lower circumferential current density and of a narrower feed gap which permits the mercury surface to be kept farther downstream. The specific heat load is further reduced by operation at the lower electron-to-atom emission ratios which now lead to optimum thruster performance (see Sec. III), and we expect to achieve additional reductions by modifications of the cathode face geometry.

III. THRUSTOR TESTING OF HIGH-TEMPERATURE LM CATHODES

Very successful demonstrations of high-temperature cathode operation in thrusters have been achieved during the past quarter.

Annular Cathode No. 25 was placed in the 15-cm diameter thruster described in Quarterly Progress Report No. 1, p. 18. This thruster has the magnetic field geometry typical for a permanent-magnet thruster, but its field is made variable by using iron-core electromagnets in place of the permanent magnet bars. The thruster end plate used had no non-magnetic insert, and the baffle used was entirely non-magnetic and was not variable in size, thus providing less-than-optimum coupling of the electron flux from the cathode into the discharge chamber. Despite these deficiencies, the following results were obtained in short ($\approx 1/2$ hour) runs:

Cathode temperature	250°C	290°C
Mass utilization	80%	90%
Source energy/ion*	400 eV/ion	790 eV/ion
Beam current	440 mA	510 mA
Cathode current	7 A	9.7 A
K_e/K_a	13	17

It should be noted that the lack of thruster optimization made it necessary to operate at relatively high electron-to-atom emission ratios and discharge currents, and that these high ratios and currents were obtained stably from the small cathode. However, this did result (as expected) in an increase of the required source energy per ion. (When all other parameters are held constant and the cathode is kept near its maximum operating temperature, the source energy per ion rises with increasing electron-to-atom ratio, discharge current, and temperature.) To improve upon this situation the thruster end plate and the baffle have been modified, but the new combination has not yet been tested.

Annular Cathode No. 26 was installed in the 20-cm diameter modified LeRC thruster which had successfully undergone a 4,000-hr life

* Excluding magnet power.

test (with an LM cathode operating at $\approx 35^{\circ}\text{C}$). Figure 1 shows cathode and discharge chamber in schematic cross section. The baffle consisted of an annular opaque zone of fixed dimensions, plus a central opaque zone of variable diameter; the axial position of the baffle was also variable. (This baffle had also been used during the last 500-hr increment of the life test.) The results obtained in short (1/2 to 1-1/2 hour) runs are listed below, together with the best performance measured with the life-test cathode in the same thruster, as described in Quarterly Progress Report No. 1.

Cathode type	Annular (No. 26)		Circular (Life Test)
Cathode temperature	250 $^{\circ}\text{C}$	300 $^{\circ}\text{C}$	35 $^{\circ}\text{C}$
Mass utilization	87%	84%	85%
Source energy/ion*	400 eV/ion	443 eV/ion	393 eV/ion
Beam current	680 mA	605 mA	600 mA
Cathode current	7.6 A	7.45 A	9 A
K_e/K_a	9.8	10.3	12.7

During the run at 300 $^{\circ}\text{C}$ cathode temperature the arc spot pattern was not a full circle, due to the feed gap geometry discussed in Sec. II. This resulted in a higher circumferential current density compared with the run at 250 $^{\circ}\text{C}$ and should account for most of the increase in source energy per ion.

The following conclusion can be drawn from the above results: Thruster performance closely approximating the best obtained with low-temperature cathodes has now been measured with a cathode operating at the temperatures required for radiative heat rejection from the thruster shell even when the thruster is part of an array. This performance was achieved simultaneously with a further reduction of the optimum electron-to-atom emission ratio, thereby compensating for most of the increased specific heat load of the cathode. It can now be expected that the planned cathode modifications will lead to a complete match of the best low-temperature performance with cathode temperatures up to at least 300 $^{\circ}\text{C}$.

* Excluding magnet power.

IV. DISCHARGE PROBING EXPERIMENTS

A 15-cm diameter thruster has been equipped with an emissive probe and a two-dimensional probe movement mechanism. The modifications to the thruster and the details of the probe construction were described in Quarterly Progress Report No. 1.

Tests were conducted in a 4-ft diameter vacuum chamber to determine probe operating points giving sufficient emission from the probe in the presence of the discharge while permitting a reasonable life of the probe. It was found that the life of the probe was severely limited by arcing to the probe. Therefore, a low-current fuse was included in the probe circuit. The fuse blowing time is fast compared to the probe destruction time thus saving the probe when an arc occurs.

Using the emissive plasma probe with all supplies and instruments either floating or coupled out through isolation transformers, plasma potential profiles were obtained both with and without beam extraction. Each profile shows the plasma potential as a function of the radius for a given plane perpendicular to the axis of the discharge chamber. All profiles taken show the same general characteristic near the cathode, a minimum plasma potential on the axis rising to a maximum near the anode. The total excursion is approximately 2.5 volts. These profiles also show a systematic shift resulting from beam extraction. That is, the plasma potential profiles increase as the beam is extracted. This behavior is consistent with the previously observed increase in discharge voltage during beam extraction.

The probe has now been adapted to the 20-cm diameter thruster in order to measure the plasma potential profile in the thruster with the best demonstrated performance.